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A REVIEW OF RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION

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ABSTRACT

Fresh water is a prerequisite for life and procreation. Water as an essential commodity is used in every phase of human life ranging from domestic activities such as drinking, cooking, washing etc. to innumerable industrial and agricultural purposes such as power generation etc. The increasing demand for fresh water by the world population today cannot be met by the available fresh water in our ecosystem. This is why numerous technologies for seawater desalination have been established and advanced over the years to augment/satisfy the ever-increasing global demand for fresh water. This paper reviews and summarizes recently published studies on desalination of seawater exploring reverse osmosis (RO) protocols, covering key areas such as seawater, desalination, reverse osmosis, RO membrane. The emphasis is on solar energy powered RO systems for seawater desalination.

KEYWORDS: Water, Reverse osmosis, Osmosis, Desalination, Seawater, Brackish Water & RO Membrane

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Original Article

1. INTRODUCTION

Water is a critical factor in the sustenance of a healthy environment in today's society. About one-third of the earth's total area is occupied by water, with around 97 % of the total water originating from the sea (Ceribasi et al., 2018). Natural sources of water are categorized into surface and sub-surface water. Surface water such as lakes, rivers etc., which account for the majority of global fresh water supply, have been seriously depleted due to below normal rainfall in recent years. Sub-surface water sources which are supposed to be more reliable have also failed due to the shortage or gradual reduction in global annual rainfall (Pangarkar et al., 2011). Over 1 billion people are estimated to be without potable water, which has resulted in over five million deaths annually from water borne diseases, of which four million are children (Pangarkar et al., 2011). Increases in population and increased demand for water means that the supply of water has become a serious problem (Greenlee et al., 2009; Pangarkar et al., 2010). Water is considered to be abundantly available, but freshwater cannot be reached easily in its unbounded cradle. Many countries globally today are suffering from immense scarcity of potable water. According to Ceribasi et al. (2018), the World Health Organization (WHO) reported that a quarter of the global population lives in regions that are not capable of accessing potable water due to lack of the basic infrastructure needed to abstract and process this water for treatment from water courses and underground natural reservoirs. Water scarcity is common around the world today, particularly in Africa and Arab countries which are the most affected regions of the world. This region is home to 6.3 % of the total world's population while it holds only 1.4 % of the world's renewable freshwater (World Health Organization). Desalination provides a solution to the incessant problem of increasing demand for potable water with limited supply. According to Karagiannis and Soldatos (2008), more than 67 % of the world's populace may be exposed to a shortage of water by 2025, spanning through all continents of the world,

including the advanced and the under-developed countries alike, unless water demand is reduced and/or alternative/additional water sources are developed. The authors comment that considering the enormous volume of seawater available, the supply capacity of any desalination system seems to be without limits. Seawater requires thorough processing to make it suitable for human consumption. Khawajia et al. (2008) estimated that more than 75 million of the world's population are accessing potable water by desalination of brackish water and seawater. The IDA Desalting Inventory (2004) reported that the total number of seawater and brackish desalination plants globally at the end of the year 2002 was 17 348 with a daily capacity of 37.8 mil/m^3 of potable water.

2. WATER SCARCITY

Water scarcity depends largely on the rate of global water withdrawal and water consumption. It was recorded by Azevedo (2014) that water scarcity is related to local requirements, which differ globally depending on the location. Ceribasi et al. (2018) reported that nearly 80 % of the world's population may be affected by water scarcity as shown in figure 1. According to Karagiannis and Soldatos (2008), about 25 % of the global population are faced with serious water shortage problems, and this is expected to result in many not having access to potable water. Desertification, global warming and drought are expected to aggravate the problem to the extent that even countries that do not face water shortages at the moment may be faced with the scarcity of potable water in the near future. It was further established, according to the World Watch Institute, that more than 67 % of the global community may witness water scarcities by the year 2025, including developed countries, with more than 80 countries projected to be affected, unless there is a reduction in the average daily water usage/demand and/or more water sources are developed. Pangarkar et al. (2011) argued that the difference between global water demand and supply has widened to the extent that in some areas this has become a severe threat to human existence. Pangarkar et al. (2010) explained that the problem of fresh water scarcity is an emerging problem globally as only a small percentage of the total water on earth is of non-saline water origin, and suitable for human consumption. Similarly, Greenlee et al. (2009) reported that a geological survey in the United States established that 96.5 % of the global water source is precipitated in oceans and seas, while only 1.7 % is contained in the ice. The residual percentage is constituted by groundwater in salty aquifers, brackish water and weakly saline water. Ceribasi et al. (2018) concluded that owing to the overwhelming presence of saline water in over 97% of the global water which are distributed in seas, oceans and other saline sources, seawater desalination has gained prominence and found acceptance as a viable substitute source of water in countries where fresh water sources are inadequate or overused. The need for fresh water globally is uppermost in the international agenda of critical problems facing the world.

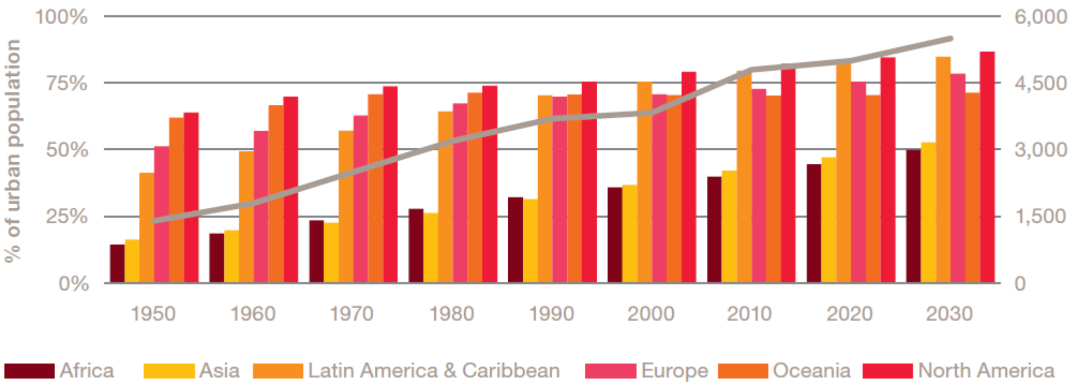

Figure 1: Population Density vs Water consumption.

Water withdrawal can be defined as the overall volume of water exploited from a river, lake or any aquifer for any reason, while water consumption is defined as the segment of withdrawn water which disappears due to the activity of vaporization, absorption or chemical conversion, transmission, or made inaccessible for additional purposes due to human usage (Azevedo, 2014). Presently, agricultural activities account for almost 70 % of global clean water withdrawals, whereas the commercial and domestic sectors are responsible for 20 % and 10 % respectively (United Nations, 2014). Industry accounts for a much larger percentage of freshwater withdrawals in developed countries, while agriculture takes the lead in water consumption in less-developed countries, accounting for over 90% of their freshwater withdrawals. Most of the statistics on freshwater withdrawal and consumption are founded on estimations rather than real measurements; according to OECD, global water withdrawals are anticipated to rise by 55 % as a result of the upsurge in manufacturing demand (400 % growth), domestic use (130 %) and thermal electricity generation (140 %) (United Nations, 2014). At the moment, about 2.8 billion of the world's population are living in areas that are prone to water scarcity, and of this figure, 1.2 billion reside in parts that are already suffering physically from water scarcity, while half a billion people are fast closing in on this situation. The remaining 1.1 billion people going through water scarcity are suffering from commercial water scarcity. This population of people lives in parts of the globe where water is naturally accessible but their access to it is limited by distribution infrastructure, institutional or financial issues, even though the available water resource is sufficient to meet their demand. This is the case in sub-Saharan Africa. Physical water scarcity arises when a water deposit in a particular locality or community is inadequate to cope with the demand of such a community, and this type of water scarcity is common in arid regions. Scarcity in other areas which are going through human-made physical water scarcity as a result of over-advance in their water withdrawal, which in turn leads to ecological degradation e.g. of groundwater tables and rivers.

3. SEAWATER AVAILABILITY

Water is an essential element of life. If water is available, life's quality and the community's economy are both enhanced. Water is one of the numerous gifts of nature. Water occupies more than half of the earth's ground surface, but, in spite of this, only around 3 % of this water is freshwater (Karagiannis & Soldatos, 2008). According to Ceribasi et al. (2014), the cost of desalinating seawater and the need to find an efficient method of desalination has challenged the scientific community to find a way out. As a result, many of the recent research studies in seawater desalination are concentrating on evolving cost-effective methods of producing freshwater for human consumption.

Azevedo (2014) reported that even though data on water precipitation are readily obtainable, it is very costly and difficult to monitor the levels of the groundwater and river runoff in many areas. Figure 2 shows 2011 regenerative water statistics (Azevedo, 2014). Regenerative water, otherwise known as renewable water, can be defined as groundwater and surface water, while deep aquifers with insignificant rate of recharging based on known human time scale are termed non-regenerative water sources (Azevedo, 2014).

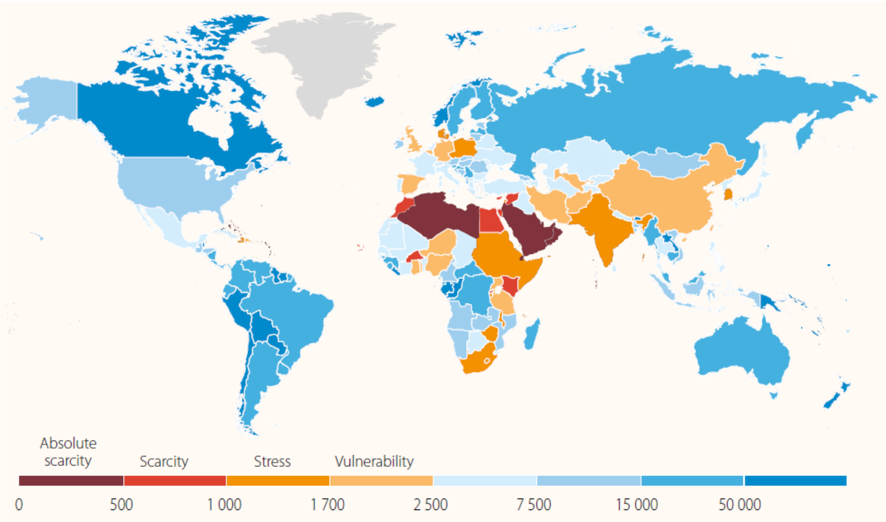

Figure 2: 2011 Statistics on Regenerative Water Resources (m3/c/yr).

4. DESALINATION

Numerous technologies or ways of desalinating seawater are being discovered and researched to augment the available fresh water supply. The techniques of desalination are divided into two classes based on the physical property of the process (Zhao, 2006). The classes are: thermal process and membrane process. Thermal technology employs the principle of liquid vaporization/evaporation to accomplish potable water separation from saline water, while membrane technology deploys the use of a filtration apparatus in bringing out potable water from saline water. Membrane technology can be further divided into reverse osmosis (RO) and electro dialysis processes, while the thermal technology is further divided into multistage flash distillation, freeze separation methods, multiple effect distillation, solar still distillation and vapor compression (Figure 3).

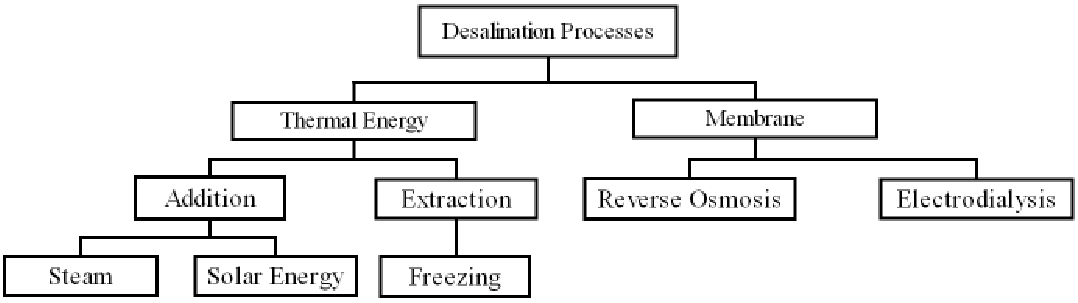

Figure 3: Desalination Technology.

Forward osmosis desalination is an evolving desalination technology which will change the overall concept of freshwater production from brackish water or seawater (Ceribasi et al., 2018). For this technology to move from the stage of laboratory research to real applications, researchers have to develop reliable novel forward osmosis membranes and draw solutes. Diverse osmotic membranes are being investigated for flux behavior. Novel draw solutes that have the capacity of easily regenerating, and which have no energy requirement for water recovery, are being researched. Kamble and Pitale (2015) examined different types of solar powered desalination systems ranging from MSF, MED, humidification-dehumidification desalination systems, electro dialysis desalination systems, solar still, and adsorption

desalination systems. and concluded that out of all these aforementioned desalination techniques, solar powered RO desalination systems predicated on solar photovoltaic technology is most commonly used and adopted, because both the PV and RO are modular and easily available. The universal installed seawater desalination capacity by technology is about 49 % and 35 % for thermal and membrane processes respectively (Pangarkar et al., 2011). According to Ceribasi et al. (2018), the development of desalination technologies has been predicated on membrane separation, thermal vaporization, electro-dialysis, etc. The authors went further to categorize desalination processes into two major types as shown in Figure 3 and Figure 4: namely: thermal desalination and membrane desalination processes.

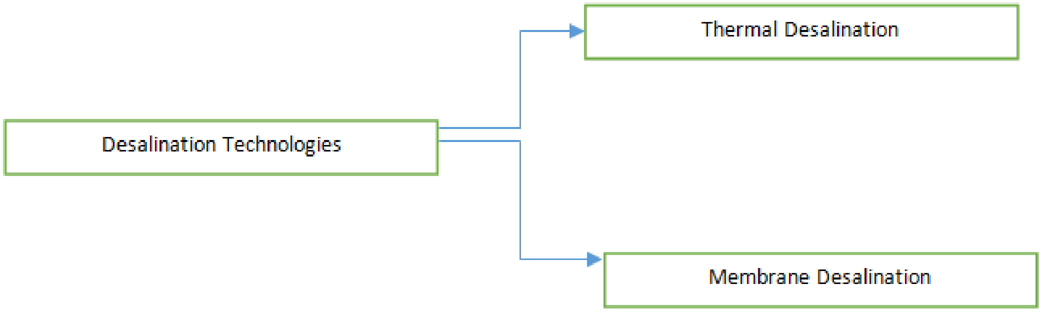

Figure 4: Desalination Processes.

The solar still is the cheapest and most affordable technique of desalination (Aybar, 2007). This is a modest device that can be used to extract potable water from dirty water, deploying solar energy as fuel. The basic principle of a solar still is that vaporized water from an open container that is left in an open area will condense back to water over a cooling surface (Figure 5).

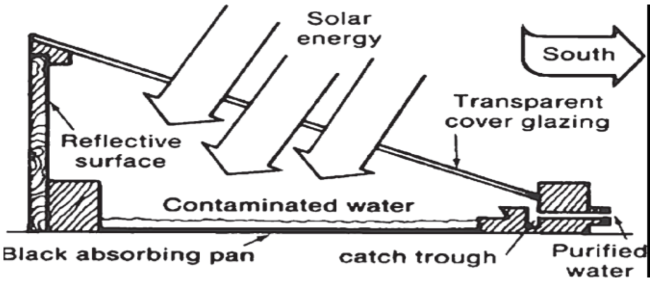

Figure 5: Solar Still Schematic.

4.1 Thermal Desalination Processes

Intake saline water from the sea or saline source is subjected to heat which produces steam that will later be cooled in order to obtain condensed water of reduced or low salt content (Ceribasi et al. 2018). Pressure is normally reduced in thermal desalination to reduce the quantity of heat required for saline water to evaporate. The Foundation for Water Research (2006) confirmed that thermal desalination processes can lower the salt content of saline water to as low as 10 milligrams per liter or even lower for TDS between 60 000 mg/L and 70 000 mg/L.

4.2 Membrane Desalination Processes

The membrane desalination process is the most frequently used in general desalination of seawater (Ceribasi et al. 2018). Membrane technology has a wide range of applications in solving sea and brackish water desalination difficulties. This

technology can be categorized based on the variety of elements involved and the mode/prime moving input deployed. The principle of membrane desalination is based on a semi-permeable membrane's ability to selectively permit molecules of water through it. The membrane desalination process can be categorized into osmosis and RO, which are the two basic desalination techniques deployed in membrane type desalination. According to (Voutchkov, 2007), scientists discovered the principle of osmosis and RO several years ago. What is relatively new is the principle of the application of RO to the desalination process. The passing of water through a semi-permeable membrane from a low concentration solution to a higher-concentration solution is what is known as osmosis. The reverse process occurs when outside pressure is applied to the higher-concentration side of the membrane, thereby diffusing the higher-concentration solution into a lower-concentration solution. Ceribasi et al. (2018) described the process by which a semi-permeable membrane allows only pure water to pass through by rejecting salt, as RO desalination. To achieve a reverse water flow, the hydrodynamic pressure should be high enough to exceed osmotic pressure when the feed water is pressured on one side of a semi-permeable membrane. This is shown in Figure 6. Williams (2003) reported that RO has been adjudged to be the most acceptable desalination technique in the world.

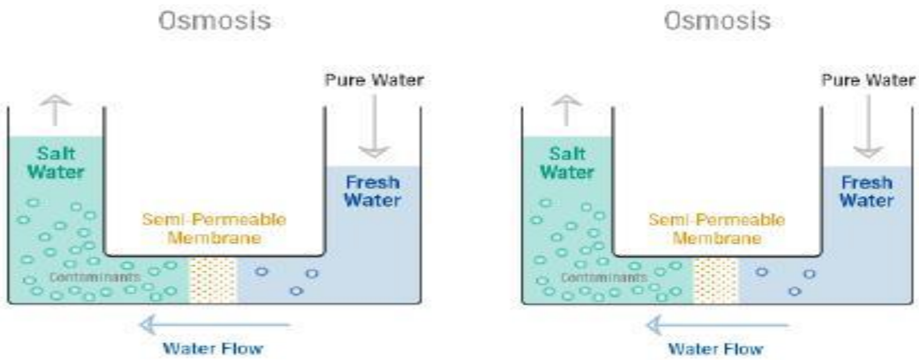

Figure 6: Reverse Osmosis.

Ceribasi et al. (2018) studied the non-stop movement of industrial RO procedures, where the application of outside force to the systems require the use of a high-pressure pump. This procedure requires the salt water to be delivered at an elevated pressure before dispensing it for membrane separation. Two diverse pressure collections are needed for saline water sources. In the case of seawater, the pressure of the intake feed needs to be raised to a pressure of 40 bar to 82 bar (600 psi to 1200 psi), and for brackish water, the intake feed pressure has to be elevated to a pressure of 2 bar to 17 bar (30 psi to 250 psi).

4.3 Reverse Osmosis Process

Saline water from the sea or brackish water sources are firstly treated with a hydraulic strainer where all floating solids that could cause a foul smell for the membrane are removed. Residual flow is then raised to the system functional pressure depending on the level of its salinity and later delivered into the desalination unit. A percentage of the water will infiltrate through the membrane and same are collected as a throughput invention after a suitable afterward treatment. The after-treatment phase will involve the normal water treatment process to ensure the potability of the treated water. Strohwald (1992) reported that RO systems in the desalination of sea-water has been studied, and adjudged to be effective. Emphasis during one of the studies was on the choice of a proficient pre-treatment system. The deployment of a low-cost tubular ultra-filtration system in combination with double media and cartridge filtration produced a very good RO residual water

with outstanding quality notwithstanding the raw water source quality. Even though fouling of ultra-filtration membranes may be noticed, the flux restoration can be achieved with the aid of sponge balls. Reverse osmosis reclamations in excess of 40 % can be achieved without harmful effects on the membranes by using a scale inhibitor. The quality of the residual water from the single stage RO unit is usually well within the endorsed SABS confines for domestic supplies with no RO membrane fouling.

4.4 Energy and Rate of Water Desalination

There are two main categories of energy sources for desalination systems: conventional sources, and renewable sources (Karagiannis & Soldatos (2008). Desalination driven by renewable energy sources may be the answer in terms of climate/ecological effect to lower energy consumption and lower CO_2 emissions. There are three major desalination systems that use renewable energy sources. These are: (a) wind, (b) solar (photovoltaics or solar collectors) and (c) geothermal. Systems powered by renewable energy sources can also be connected to a conventional source of energy (e.g., local electricity grid) in order to reduce the variations in the level of energy production and consequently water production.

Multi-effect distillation (MED) remains the most used thermal methods, i.e., vapor compression (VC) / multi-stage flash (MSF). RO is the most widely accepted membrane method. Thermal methods when compared to the membrane method seem to be more efficient in terms of effective desalinating of salty seawaters, but critical studies have found that thermal methods are more expensive due to the large quantity of fuel required for vaporization of the salt water. Membrane methods which are mainly RO have the ability to desalt brackish water more economically, and have substituted in popularity the use of thermal methods for desalination. However, due to the high cost of membrane replacement, membrane methods are not frequently used for desalination. The American Membrane Technology Association (2003) reiterated that technological development has aided the decrease in the total desalination cost, by refining the energy efficiency (multi-flash distillation or hybrid systems), and by improving the transfer processes or energy recycling (process of cogeneration).

5. REVERSE OSMOSIS

Desalination system technologies are an excellent technique for generating large volumes of standard potable water at a reasonably competitive cost, but the high energy consumption remains a major setback to the system (Pangarkar et al. 2011). The latest membrane technological discoveries, e.g., RO, nano-filtration (NF), and electro dialysis (ED), have in recent times gained recognition due to their reliable separation capabilities and potential for water treatment. RO membrane technology has been widely adjudged the lead technology for desalination installations, and is suitable for both brackish and seawater usage. Brackish water desalination (RO membranes) are typically identified with higher water flux, lower salt elimination, and require less operational pressures due to the reduced osmotic pressure (M'nif et al., 2007). However, this system is usually associated with some problems because of the creation of polarization films and by-products which may produce bacteria and pollution. According to Pangarkar et al. (2011), this problem can be overcome by deploying alternative membrane technology such as membrane distillation for underground water desalination. Generally, RO membrane treatment processes are designed to either use pressure or conventional electrical driven technologies. The pressure-driven membrane mode of operation can be divided into four categories, namely: RO, ultra-filtration (UF), micro-filtration (MF) and nano-filtration (NF). Nano-filtration process are considered to be efficient in salt desalination. Poullikas (2001) categorized a typical RO system into four major sub-systems: (a) pre-treatment system, (b) high-pressure pump, (c) membrane module, (d) post treatment system. The pre-treated feed water is channeled to flow

across the membrane surface, when a high-pressure pump is deployed. The operating pressure of RO ranges between 17 bars and 27 bars for brackish water and between 55 bars and 82 bars for seawater. According to Strohwald (1992), since the development of asymmetric cellulose acetate membranes by Loeb and Sourirajan in the early 1960s, RO membranes have been used commercially for sea water desalination. The author reported that most of the major membrane producers, e.g., DuPont (USA), Filmtec (USA), and Toyobo (Japan), manufacture membranes from synthetic polymers made specifically for the desalination of seawater. Water production from seawater through the RO technique gained significant popularity in the mid-seventies with new desalination installations springing up around the world. The author points out that the operating cost of RO desalination is lower than MSF evaporation since no phase change is involved. Economics, high energy consumption and improvements in the RO technology development caused a sharp decline in the market share of MSF evaporation from 67 % recorded in the early 1980s to 3 % in 1989, while RO made an equivalent rise from 23 % to 85 % during the same period (Ahmed, 1991). Water resources are speedily being depleted, and this has resulted in more attention being paid to desalination of sea and brackish water (Raju Yadala & Ravinder, 2018). In the present day, much energy is required for desalination, making it less cost friendly. According to Tzen (2006), RO is the most used and most economic method of desalinating brackish water. However, other methods exist but are seldom used. One example though, is on Kimolos island, Greece, where the MED process utilizes the abundant geothermal energy in the island to generate 80 m^3/day of potable water at 2.00 h/m^3.

The brackish total dissolved solids (TDS) can and do affect the cost of water produced per day which varies from 2000 ppm to 10 000 ppm. Raju Yadala and Ravinder (2018) compared the cost of 230 ppm brackish water desalination in Jordan that is as low as 0.21 h/m^3 (0.26 \$/m^3) to 5000 ppm brackish desalination in Florida at 0.22 h/m3 (0.27 \$/m3), and it was established that two similar systems that uses dissimilar water volume of TDS usually have a considerable cost disparity. Tzen (2006) argued that the desalination of 10 000 ppm brackish water using conventional sources of energy costs 0.43 \$/m3, while using renewable energy sources in similar situation will cost as high as 8.2\$h/m3 (10.32\$/m3].

The cost of water production from desalination schemes using conventional sources of energy, (gas, oil, electricity) is lower and cheaper when compared to renewable sources of energy over a short period, but when considered over a long period of time, renewable energy is practicably cheaper. The RO method of desalination as shown in figure 7 has become more prevalent past few years because the cost of membranes has become more affordable. Some years ago, RO was mainly utilized for desalination of brackish water, but of late it has become the most commonly used method for various kinds of desalination due to its lower energy demands. Therefore, RO is now being applied to larger units that have the ability to deliver daily production of 320 000 m^3.

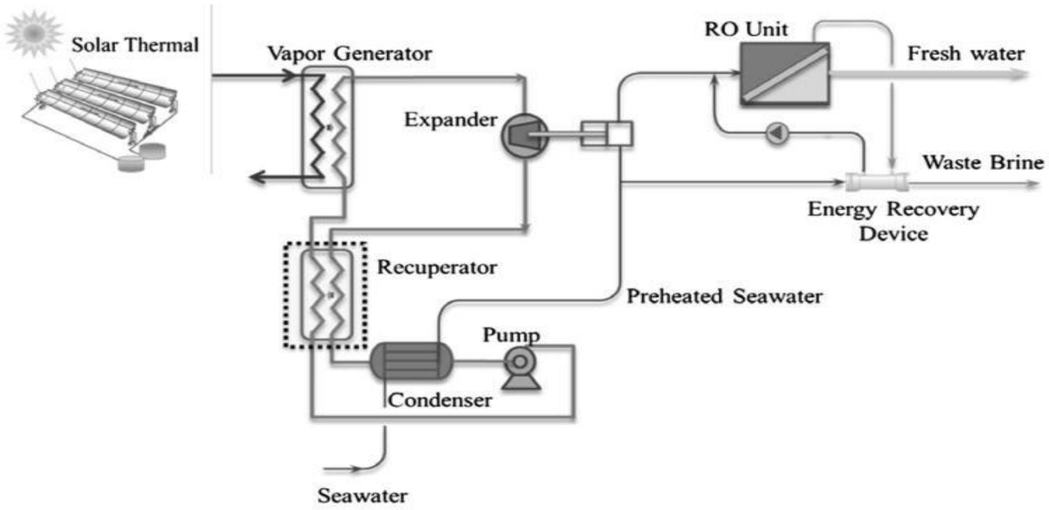

Figure 7: Reverse Osmosis.

5.1 Basic Principles of Reverse Osmosis Process

According to Greenlee et al. (2009), in RO and nano-filtration, osmosis is said to take place when water flows from a diluted salty solution, and passes over a semi-permeable membrane into a section of higher concentrated saline solution. A semi-permeable is penetrable to pure water but does not allow salty liquid to penetrate. On the assumption that a membrane can only allow passage of water and not salt, when there is a salt solution in one section and pure water in another section, a semi-permeable membrane will permit water to permeate through it to either side, but salt will not be allowed. Greenlee et al. (2009) defined osmotic pressure in RO as the ultimate height difference between water columns when water diffuses towards a higher concentration through a semi-permeable membrane from a region of lower concentration in order to equalize the solution strength, and RO reverses water flow direction when the applied pressure is in excess of the osmotic pressure. To achieve desalination, the system will try to maintain an equilibrium position by allowing water to flow from the clear water to salt solution compartment in order to equalize the level of concentration on both sides of the membrane and dilute it. An increase in the level of salt solution may be created by osmosis and will continue to increase until the water column pressure (salt solution) becomes so high that the force of the water column stops the inflow. The water level equilibrium point in terms of the pressure from the water against the membrane is called osmotic pressure (Figure 8 and Figure 9).

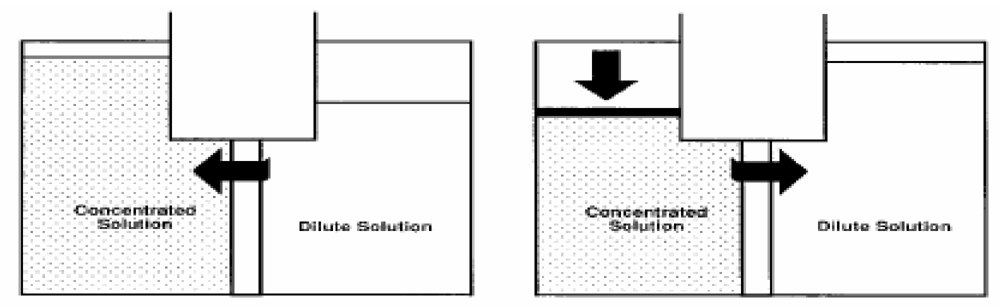

Figure 8: Overview of Osmosis.

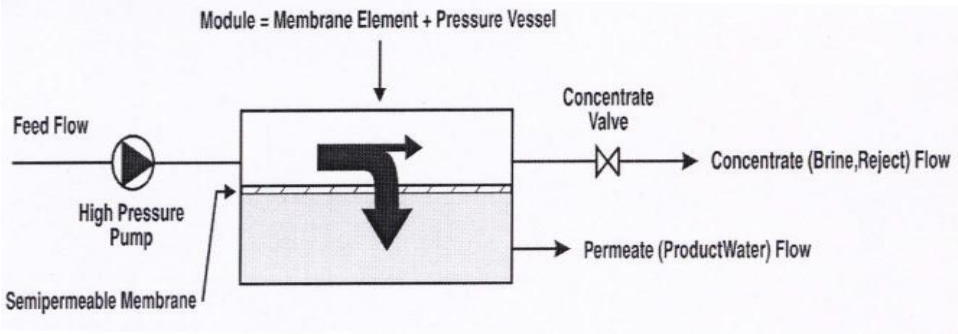

Figure 9: Reverse Osmosis Process.

When a force is applied to the column of water, and the direction of water flowing through the membrane is reversed, this process is known as reverse osmosis. It should be noted that since the membrane is not permeable to salt, the reversed flow produces pure water from the salt solution (Greenlee et al., 2009). Manolakos et al. (2005) described RO as a physical procedure that adopts the osmosis concept using osmotic pressure difference between the saline water and the clear water to remove salt from water. Raju Yadala and Ravinder (2018) also described RO as a process where an intake stream flows under a higher pressure through a semi-permeable membrane thereby segregating two aqueous streams, one brine (rich in salt) and other clear water (lacking salt). According to Tian et al. (1999), as the exerted pressure is higher than the osmotic pressure, clear water will permeate through the membrane and brine will be collected as a byproduct of the system. Consequently, water with low salt concentration stream, will permeate through the membrane and concentrated brine will remain inside the feed part of the system. According to Raju Yadala and Ravinder (2018), when compared to sea water, brackish groundwater usually has a much lower osmotic pressure, and as a result, its desalination process requires less energy. Low-cost plastic components are allowed in an RO system due to the lower pressure associated with brackish water. Tzen (2006) reported that RO membranes are made of a polymer material which forms a coated, web-like structure. Feeds with elevated pressure are made to run through a circuitous pathway to the membrane, and then to the permeated side. According to Maalouf (2014), RO membranes usually offer high salt rejection membranes for RO plants. Membranes are designed for a normal lifetime of 7 years with an effective pre-treatment. The salt passage through a membrane can be affected by the cleaning methods, salinity, temperature, and target recovery. TDS levels has to be reduced to convert seawater into safe drinking water (properties shown in table 1), and this can only be achieved by using either old desalting technologies or desalination processes which use newer technology such as sea water RO (SWRO), electro dialysis (ED), electrode-ionization (EDI) multi-effect distillation (MED) and multi-stage flash (MSF) distillation. A hybrid setup can be created by combining some of these desalination processes in some instances, to achieve the best desalination and also reduce energy consumption.

Table 1: Potable Water Organoleptic Properties (World Health Organization, 2003)

Concentration (MG/L)	Classification
TDS ≤ 300	Excellent
300 ≤ TDS ≤ 600	Good
600 ≤ TDS ≤ 900	Fair
900 ≤ TDS ≤ 1,200	Poor
TDS > 1,200	Unacceptable

5.2 Reverse Osmosis Membrane Fouling

Raju Yadala and Ravinder (2018) point out that RO membrane fouling has become a major problem in the application of RO in the potable water production industry, and this is more pronounced when high concentrations of organic matter and inorganic constituents occur. The authors also note that membrane fouling is generally triggered by organic components (humic acid) or melted inorganic (BaSO4, CaSO4, and CaCO3) suspended particles, bacteria, or floating solids. Turek and Dydo (2003) classified pollution into organic, inorganic, and biofouling, and the polluting deposits mainly comprise a mixture of organic matter, iron, phosphorous, and microorganisms, combined with chemical constituents in seawater or surface water. Pangarkar et al. (2011) concluded that the acute fouling problem associated with the brackish RO system is usually salt precipitation and membrane scaling. The authors also reported that concentration polarization is the key factor to be considered in membrane pollution of melted inorganic contaminants Fouling escalates resistance, which, as a consequence, reduces infiltrated flux. The resistance responsible for reducing the flux are: membrane resistance (*Rm*), concentration polarization resistance (*R*cp), cake resistance (*Rc)*, and pore blocking resistance (*Rp*). The total resistance during membrane filtration can be taken as:

$$RT = Rm + R\text{cp} + Rc + Rp. \qquad \text{Equation (1)}$$

Membrane types can either be porous or nonporous, which is a key factor in defining the flux resistance triggered by inorganic fouling; *Rp* is not applicable to non-porous membranes. The primary technology/techniques always deployed in controlling fouling are the feed pretreatment and membrane cleaning. Reducing the fouling tendency of the water in the system is the main objective of any RO pretreatment system for seawater or brackish water.

5.3 Energy Requirements and Recovery

Raju Yadala and Ravinder (2018) confirmed that seawater or brackish water desalination technology is the best method for producing large quantities of potable water at a competitive cost, but the high energy consumption of this system remains a problem. Muthumariappan (2004) stated that a flow rate is proportionally related to the feed pressure required to pump the water; this same energy is the primary energy used in the RO system. High brine concentration in seawater requires high hydrostatic pressure of up to 7 000 kPa to produce the desired permeate flux; the higher the salt concentration, the greater the pressure and the pumping power required. The energy cost center in the RO process is the high-pressure pump set which is approximately 70 % of the total energy requirement, and the applied hydrostatic pressure must be higher than the osmotic pressure of the water feed segment of the membrane. The osmotic pressure on the feed compartment of the membrane continues to increase when the (RO) unit recovery work increases, thereby increasing the required feed pressure. The resultant brine waste from the system is characterized by high pressure and having shared a considerable percentage of feed pressure. This resultant brine pressure can be profitably utilized to enhance the feed pressure of the raw water by deploying an appropriate technology, and this process is called the energy recovery system.

6. DESALINATION ENERGY DEMAND

Azevedo (2014) confirmed in his study that the desalination process is considered to be an energy demanding process, as it consumes more energy per liter when compared to other water supply treatment options. The energy required for the desalination process varies and is hinged on other factors including facility design, deployed technology, feed water quality and temperature, the application of energy recovery devices / the quality of the projected water produced. Technological advancement has reduced the energy demands of desalination over the last 40 years, and this trend is expected to increase

because technology keeps evolving. The areas to develop in order to minimize energy consumption in desalination are: (a) Improved system design (b) High efficiency pumping (c) Energy recovery (d) Innovative membrane materials and (e) Advanced technologies. The energy consumption in membrane desalination processes depends mostly on the recovery rate and the feed water salinity. In the RO process, the energy required in the system is for pumping of the feed water. The average energy consumption of a RO process varies, ranging between 3.7 kWh/m3 and 8 kWh/m3 for seawater depending on the size of the facility. For a seawater RO unit of 24 000 m^3/day the average energy consumption varies between 4 kWh/m3 and 6 kWh/m3 with energy recovery devices. On the other hand, the brackish water RO unit average energy consumption ranges between 1.5 kWh/m3 and 2.5 kWh/m3 (Al-Karaghouli & Kazmerski, 2013).

7. RENEWABLE ENERGY-POWERED DESALINATION

All over the world, desalination of sea and brackish water has gained acceptance for supply of potable water. Some inaccessible villages in third world countries are isolated from the main cities and as such often lack access to the national electricity grid which has created a big vacuum in accessibility to potable water supply, which are usually powered by conventional electricity. Similarly, in order to reduce their environmental impact, desalination facilities require an energy source that is low in emissions and at the same time affordable. Renewable energy sources such as solar photovoltaic, wind, thermal or geothermal energy can be exploited to solve these problems. The International Energy Agency (2012) justified renewable energy for desalination in order to reduce greenhouse gases emission as the current capacity of desalination worldwide exceeds 70 million m^3/day. Similarly, renewable energy cost solutions are expected to further depreciate, the remote villages and locations with low population and poor infrastructures are expected to be attracted and gain access to potable water. Renewable powered desalination plants/facilities at present, represents less than 1 % of the global desalination capacity, and most of these desalination plants are RO based technology measuring about 62 % of the world capacity followed by MSF and MED. Solar photovoltaic (PV) is the leading renewable energy source for water desalination facilities, and it accounts for 43 % of the total desalination plants, followed by thermal and wind energy (Azevedo, 2014). The practicability of renewable energy plant depends largely on various factors, including feed water salinity, location, availability of renewable energy sources, plant capacity/ the availability of national electricity grid.

7.1 Solar Photovoltaic

Solar photovoltaic (PV) systems work to transform sun energy into direct current by using semi-conductors and PV cells. The PV modules are made up of PV cells which produce direct current that is accumulated and stored in batteries or directly fed into an inverter, which converts the direct current into alternating current (Azevedo, 2014). The solar PV systems are directly connected to RO desalination for the pumping system. The system is made up of a set of batteries for energy storage, and a charge controller that protects and regulates the charging of the batteries by circumventing deep discharges and overcharge. The battery set enables the membrane system to generate a certain quantity of water at the desired quality and avoid variations in pressure and flow. The effects of large variations relating to solar irradiance in battery-less membrane systems, is the major issue that necessitates an urgent need for research. Practical experiments have shown that the system can produce good quality water, although this will depend on the type of membrane used. Another significant issue in RO desalination is the ability of the system to function at variable capacities, based on the available energy. Ghafoor et al. (2020) discussed the new RO technology developed by ENERCON GmbH in which a piston system is used for energy recovery, and also permits variable levels of energy input. Reverse osmosis systems operating with this new technology can vary the production output between 12.5 % and 100 % of normal capacity by varying the piston speed

and regulating the production for available energy input or water demand. Other companies are also researching and developing systems that have this demand response capability. Ghafoor et al. (2020) conducted a feasibility on 500 L/h capacity solar powered RO desalination system and concluded that the productivity of any membrane appreciated with every increment in the temperature of the feed water resulting in a permeate productivity of 60 % and brine of 40 %. Helal (2008) conducted an economic analysis study and performance evaluation on a RO system using a PV system with no battery accumulator, just PV and a diesel generator. The results of the studies indicated that 20 m^3/d throughput was obtained using PV-RO combined with diesel, 20 m^3/d throughput deploying only the diesel generator, and 44 m^3/d water throughput was gained using solar based RO only on clear sunny days, Figure 10 shows a schematic diagram of a PV-RO system. Bilal (2016) conducted a study on a PV system with battery and without battery for operation of an RO system. The results showed that 5.9 L/h permeate productivity was produced with battery for 5 h and 3.8 L/h without battery. The fresh water throughput was 9.8 % higher with a battery dependent PV system in comparison without a battery system. The authors concluded that both types of PV systems were beneficial but battery-less was more economically suitable compared to battery-based systems.

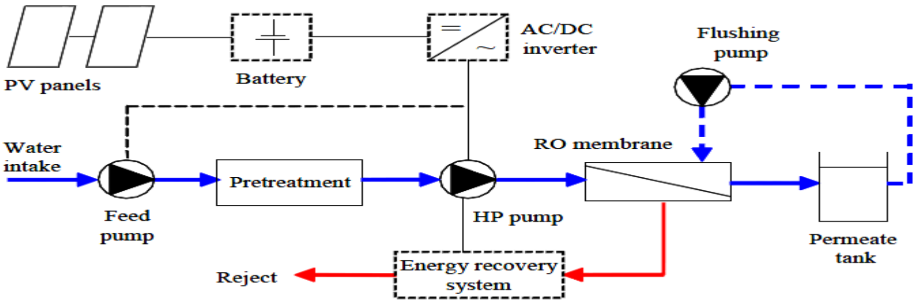

Figure 10: Schematic of PV-RO System.

Azevedo (2014) concluded that PV-RO system as shown in figure 10 has been considered one of the most robust options for renewable energy powered desalination, especially for remote areas, as both PV and RO are modular and accessible. The modularity contributes to the reduction in cost that has been achieved via economies of scale, and permits small-scale systems that can be achieved by attaching a DC output of PV modules directly to DC pumps and electronics, thereby increasing the overall efficiency of the system by 5 % to 10 % due to the prevention of losses in DC-AC power conversion and AC-DC rectification (Richards & Schafer, 2009). Figure 11 shows a schematic of a PV-ED system

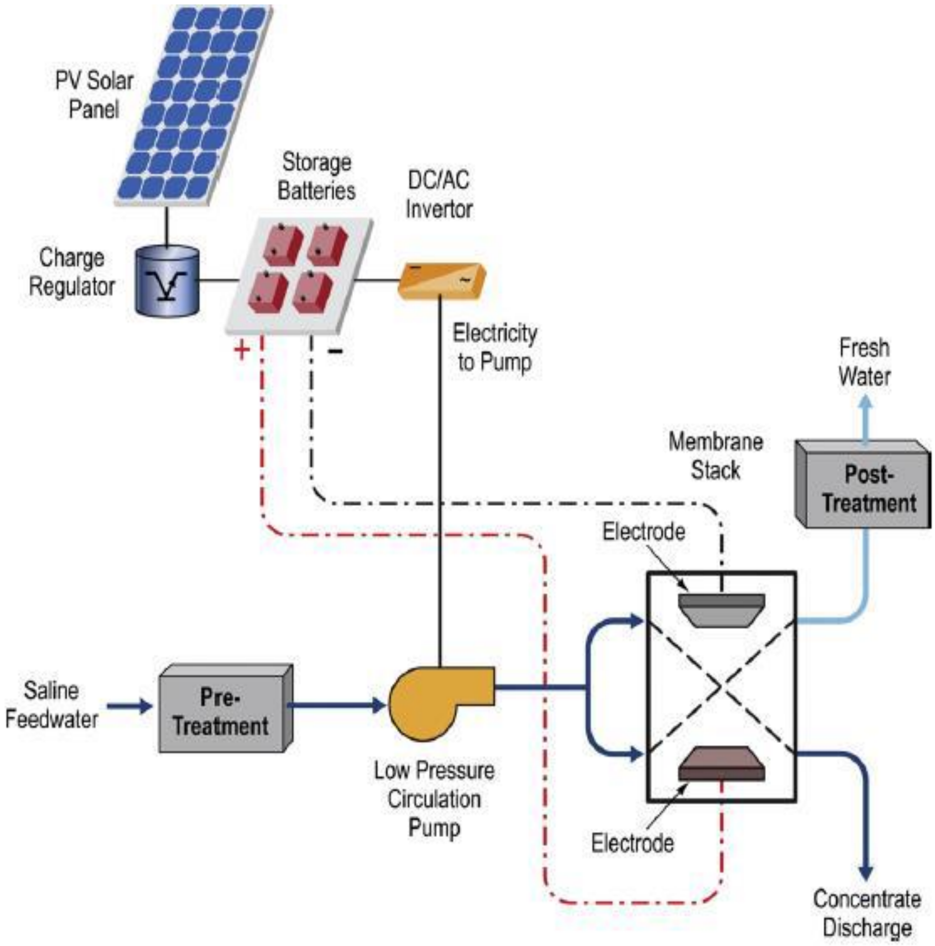

Figure 11: Schematic of PV-ED System.

8. HOW MANY COUNTRIES ARE PRACTISING RO DESALINATION

Strohwald (1992) reported that as of 1992, the installed world-wide RO capacity is estimated at 13 297 000 m/day This figure includes both seawater and brackish water desalination applications. Others are, 20 000 m^3/day plant at Ghar Lapsi, Malta (DuPont, 1986a) and the 46 000 m^3/day plant at Ras Abu Jarjur, Bahrain (DuPont, 1986b).

Up to 2009, many RO facilities, with different capabilities ranging from 100 m^3/day to 9 000 m^3/day, have been constructed in the Republic of South Africa for the desalination and treatment of brackish waters and industrial effluents. Greenlee et al. (2009) cited the new 36 m/g/d (136380 m3/day) seawater RO plant in Singapore as the largest in Asia and one of the largest in the world. The authors further confirmed that the RO systems for industrial and residential needs are being produced by various companies. The Saudi Arabian Saline Water Conversion Corporation (SWCC) has concluded a plan to upgrade the desalination plant in the country and build a new one with a larger capacity. Desalination has become a significant solution to Algeria’s water demand. The Chennai Water Desalination Ltd. was established to produce a 100 m/l/d desalination throughput plant at Kattupalli village in Tamil Nadu, India (Water Today, 2006). Raju Yadala and Ravinder (2018) stated that 48 % of the total number of global RO plants are of brackish water source, while 25 % are of seawater source, and the remaining 27% desalination plants comprise other feed waters such as streams, wastewater, and unpolluted water.

9. WHAT ARE THE FUTURE CHALLENGES

Strohwald (1992) reported that RO units are capable of producing potable water of standard quality, but this technology always comes with the problem of premature decline in capacity and salt rejection performance. This can be attributed to an operational problem with pretreatment and maintenance systems, which may result in the membranes being subjected to the following:

- Chlorine escaping from the pretreatment section
- Bacterial contamination
- Membrane fouling which may not have been removed during pretreatment and could not be also detected by the plugging index determination
- Contamination by grease from pump

Based on a recent investigation of desalination of sea-water for potable water production in one of the naval applications, the following system design/operational problems were identified:

- *Pulsation and noise from high pressure pumps*. Several problems were reported with high pressure positive displacement pumps, ranging from failed bearings, cracked plungers, and valve pitting to water leaks past the plunger pump packing. It was also reported that incorrect sizing and routing of inlet plumbing and heavy vibration from pumps might have have initiated damage to some of the DuPont preemptors, which may cause high mechanical noise and cavitation. All the problems identified underline the need for right sizing of the suction and discharge piping, and also, the finest positioning of pulsation dampeners must be put into consideration at the design stage(Strohwald 1992).
- *High pressure pumps.* Wrong selection for the specific duty and operation of the pumps may result in excessive vibration and eventual breakdown, and also complications in the procurement of spares for imported pumps can cause problems. There is a need for selecting best fit pumps specifically designed and engineered for RO applications.
- *Pre-treatment.* Insufficient and unsuitable pretreatment equipment has led to premature RO membrane fouling with consequential reduction in capacity and product quality. These particular problems have led to the wrong perception of RO being unreliable and unnecessary expensive, even though the ability of the system to produce potable water from seawater and brackish water is unquestionable. This misconception can only be addressed by showcasing the competences of appropriately engineered plants in the market (Strohwald 1992).
- *Bacterial control.* Extreme precaution must be exercised when deploying chlorine as a bactericide to prevent a scenario of chlorine breakthrough from the pretreatment section. Although chlorine may be considered very effective in preventing bacterial development, RO membranes are very sensitive to chlorine, and as such, chlorine breakthrough is fatal to the performance of the RO membranes.

10. CONCLUSIONS

This paper reviewed RO as being an excellent desalination technology. It is the most popular membrane technology for seawater and brackish water desalination and can produce large quantities of standard portable water at an economical cost.

The main drawback, however, is that an RO system requires high energy consumption. Also reviewed is the economic viability of renewable energy powered RO systems and other desalination techniques for sea and brackish water, energy costs, properties of RO membranes and challenges facing RO membrane system construction.

This paper summarizes the solar powered RO processes and basic principles behind the RO membrane technology with the goal of establishing and promoting the advantages of photovoltaic (PV) RO membranes over other methods, and to bring to the fore the only shortcoming of the system (high energy consumption) with the aim of encouraging further studies to eliminate it.

REFERENCES

1. *Al-Karaghouli, A. & Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renewable and Sustainable Energy Reviews, 24, 343–356.*
2. *American Membrane Technology Association. (2005). How much does desalted water cost? Retrieved from https://www.chainaris.co.th/sites/5086/files/u/download/knowledges/Reverse%20Osmosis/desalination%20cost.pdf*
3. *Aybar, H. S. (2007). A review of desalination by solar still. Chapter in NATO Security through Science Series C: Environmental Security May 2007, DOI: 10.1007/978-1-4020-5508-9_15*
4. *Nkh strohwald, Pilot Scale Desalination of Sea-water by Reverse Osmosis. Water Research Commission, wrc report no 345/1/92, ISBN 1 874858 41 1, 1992*
5. *Azevedo, F. D. A. S. M. (2014). Renewable energy powered desalination systems: Technologies and market analysis. Master's dissertation, University of Lisbon.*
6. *Bilal, H., Alami, A. H., Farooq, M., Qamar, A., & Siddiqui, F. A. (2016). The economic analysis of portable photo-voltaic reverse osmosis (PVRO) system. Technical Journal, 21(II), 1–6.*
7. *Ceribasi, G., Al-Najjar, H, & Aytulun, U. (2018). Overview of water desalination technologies. Conference: III. Uluslararası Mesleki ve Teknik Bilimler Kongresi (UMTEB – III), Turkey. Retrieved, from https://www.researchgate.net/publication/335542921*
8. *Foundation for Water Research. (2006). Desalination for water supply. Marlow, U.K.: Foundation for Water Research.*
9. *Ghafoor, A. Ahmed, T., Munir, A., Arslan, C. & Ahmad, S. A. (2020). Techno-economic feasibility of solar based desalination through reverse osmosis, Desalination, 485(1). https://doi.org/10.1016/j.desal.2020.114464*
10. *Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. & Moulin, P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Research, 43(9), 2317–2348.*
11. *Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. & Moulin, P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Research, 43(9), 2317–2348.*
12. *Helal, A. M. (2008). Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates, Desalination, 221(1–3), 1–16.*
13. *IDA Desalting Inventory. (2004). Desalination business stabilized on a high level. International Desalination and Water Reuse, 14, 14–17.*
14. *International Renewable Energy Agency (IRENA) (2012). Water desalination using renewable energy. IEA-ETSAP and IRENA.*

15. *Kamble, S. M. & Pitale, A. D. (2015). A review on solar powered desalination systems, International Journal of Engineering Research & Technology, 4(3).*
16. *Karagiannis, C. & Soldatos. P. G. (2008). Water desalination cost literature: Review and assessment. Desalination, 223, 448–456.*
17. *Ioannis C. Karagiannis*, Petros G. Soldatos, Water desalination cost literature: Review and assessment. ScienceDirect, Desalination 223 (2008) 448–456*
18. *A.D. Khawajia, A. D., Kutubkhanah, I. K., & Wie, J. (2009). Advances in seawater desalination technologies. Desalination, 221, 47–6.*
19. *M'nif, A., Bouguecha, S., Hamrouni, B. & Dhahbi, M. (2007). Coupling of membrane processes for brackish water desalination, Desalination, 203(1–3), 331–336.*
20. *Maalouf, S. (2014). Planning and design of desalination plants effluent systems. Doctoral thesis, University of California, Los Angeles.Retrieved from https://escholarship.org/uc/item/60f4s0qn*
21. *Manolakos, D., Kyritsis, S.,Papadakis, G., Karagiannis, J., & Soldatos, P. (2005). Cost analysis and economic evaluation of an autonomous low-temperature solar rankine cycle system for reverse osmosis desalination — Comparison with a simple solar still desalination system. WSEAS Transactions on Environment and Development, 1.*
22. *Muthumariappan, L. (2004). Energy conservation systems in reverse osmosis desalination plants. TWAD Technical Newsletter, January, 2004.*
23. *Pangarkar, B. L., Sane, M. G. & Guddad, M. Reverse osmosis and membrane distillation for desalination of groundwater: A review. International Scholarly Research Network ISRN Materials Science. doi:10.5402/2011/523124*
24. *Pangarkar, B. L., Thorat, P. V., Parjane, S. B., & Abhang, R. M. (2010). Performance evaluation of vacuum membrane distillation for desalination by using a flat sheet membrane. Desalination and Water Treatment, 21(1-3), 328–334.*
25. *Poullikas, A. (2001). Optimization algorithm for reverse osmosis desalination economics. Desalination, 133, 75–81.*
26. *Raju Yadala, K. & Ravinder, R. (2018). Reverse osmosis plant design and evaluation-A case study. International Journal of Latest Trends in Engineering and Technology,10(3), pp.001-006*
27. *Richards, B. S. & Schafer, A. I. (2009). Renewable energy powered water treatment systems. In: Escobar, I. C., Schäfer, A. I. (Eds.). Sustainable water for the future – Water recycling versus desalination (pp. 353-371). Elsevier.*
28. *Strohwald, N. K. H. (1992). Pilot scale desalination of sea-water by reverse osmosis. Water Research Commission, WRC Report no 345/1/92.*
29. *Tian, J., Shi, G., Zhao, Z. & Cao, D. (1999). Economic analyses of a nuclear desalination system using deep pool reactors, Desalination, 123, 25–31.*
30. *Turek, M. & Dydo, P. (2003). Hybrid membrane-thermal versus simple membrane systems, Desalination, 157, 51–56.*
31. *Tzen, E. (2006). Renewable energy sources for desalination. Paper presented at Workshop on Desalination Units Powered by RES, Athens.*
32. *United Nations World Water Assessment Programme. (2014). The United Nations World Water Development Report 2014: Water and Energy. Paris: UNESCO.*
33. *Voutchkov, N. (2007). Advances in seawater desalination techniques. Water conditioning and purification, Stamford, CT: Poseidon Resources Company, 2007*

34. *Williams, M. E. (2003). A brief review of reverse osmosis membrane technology. EET Corporation and Williams Engineering Services Company, Inc.*
35. *Zhao, Y. (2006). Reverse osmosis desalination in a mini renewable energy power supply system. Master's dissertation, Curtin University of Technology.*
36. *Ncube, Randy, and Freddie L. Inambao. "Experimental Data Analysis for a Reverse Osmosis Desalination Plant." International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 11.3: 421-440.*
37. *AL-Solami, Mazen A. "Seawater Desalination Using Smart Polyacrylic Acid Hydrogel In Haqel-Tabuk, Kingdom of Saudi Arabia (KSA)." International Journal of Zoology and Research (IJZR) 8 (2018): 1-8.*
38. *Ruban, M., S. Sivaganesan, and C. Dhanasekaran. "Experimental Investigation on Straight through Solar Salt Water Desalination System Analysis in Different Pcm Materials." International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8.3, Jun 2018, 67-80*
39. *Sudhakar, M. "Selection of an Efficient Desalination Technology to Treat Brackish Water for Domestic Application in Metropolitan Cities in India using Multicriteria Analysis." International Journal of Industrial Engineering & Technology (IJIET) 9.1, Jun 2019, 39-54*